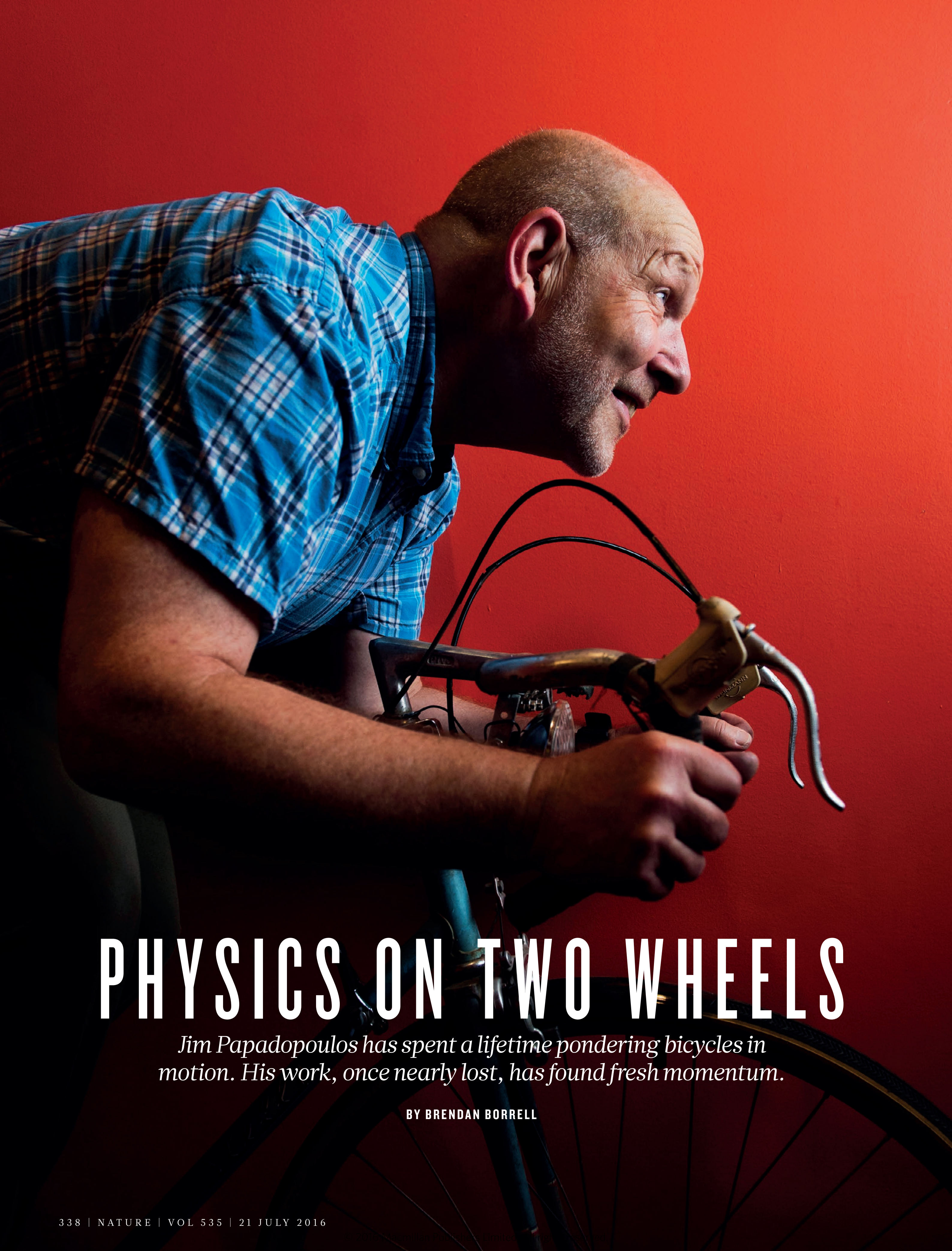


PHYSICS ON TWO WHEELS

Jim Papadopoulos has spent a lifetime pondering bicycles in motion. His work, once nearly lost, has found fresh momentum.

BY BRENDAN BORRELL

Seven bikes lean against the wall of Jim Papadopoulos's basement in Boston, Massachusetts. Their paint is scratched, their tyres flat. The handmade frame that he got as a wedding present is coated in fine dust. "I got rid of most of my research bikes when I moved," he says. The bicycles that he kept are those that mean something to him. "These are the ones I rode."

Papadopoulos, who is 62, has spent much of his life fascinated by bikes, often to the exclusion of everything else. He competed in amateur races while a teenager and at university, but his obsession ran deeper. He could never ride a bike without pondering the mathematical mysteries that it contained. Chief among them: What unseen forces allow a rider to balance while pedalling? Why must one initially steer right in order to lean and turn left? And how does a bike stabilize itself when propelled without a rider?

He studied these questions intensely as a young engineer at Cornell University in Ithaca, New York. But he failed to publish most of his ideas — and eventually drifted out of academia. By the late 1990s, he was working for a company that makes the machines that manufacture toilet paper. "In the end, if no one ever finds your work, then it was pointless," he says.

But then someone did find his work. In 2003, his old friend and collaborator from Cornell, engineer Andy Ruina, called him up. A scientist from the Netherlands, Arend Schwab, had come to his lab to resurrect the team's research on bicycle stability.

"Jim, you need to be a part of this," Ruina told him.

TWO WHEELS GOOD

Together, the researchers went on to crack a century-old debate about what allows a bicycle without a rider to balance itself, publishing in *Proceedings of the Royal Society*[1] and *Science*[2]. They have sought to inject a new level of science into the US$50-billion global cycling industry, one that has relied more on intuition and experience than on hard mathematics. Their findings could spur some much needed innovation — perhaps helping designers to create a new generation of pedal and electric bikes that are more stable and safer to ride. Insights from bicycles also have the potential to transfer to other fields, such as prosthetics and robotics.

"Everybody knows how to ride a bike, but nobody knows how we ride bikes," says Mont Hubbard, an engineer who studies sports mechanics at the University of California, Davis. "The study of bicycles is interesting from a purely intellectual point of view, but it also has practical implications because of their ability to get people around."

For a mechanician — that fusty breed of engineer whose subject is defined by Newton's three laws of motion — the conundrums of the bicycle hold a special allure. "We are all stuck in the nineteenth century, when there wasn't such a difference between math and physics and engineering," says Ruina. Bicycles, he says, are "a math problem that happens to relate to something you can see".

The first patents for the velocipede, a two-wheeled precursor to the bike, date to 1818. Bikes evolved by trial and error, and by the early twentieth century they looked much as they do today. But very few people had thought about how — and why — they work. William Rankine, a Scottish engineer who had analysed the steam engine, was the first to remark, in 1869, on the phenomenon of 'countersteering', whereby the rider can steer to the left only by first briefly torquing the handlebars to the right, allowing the bike to fall into a leftward lean.

The link between leaning and steering gives rise to the bicycle's most curious feature: the way that it can balance while coasting on its own. Give a riderless bike a shove and it may wend and wobble, but it will usually recover its forward trajectory. In 1899, English mathematician Francis Whipple derived one of the earliest and most enduring mathematical models of a bicycle, which could be used to explore this self-stability. Whipple modelled the bicycle as four rigid objects — two wheels, a frame with the rider and the front fork with handlebars — all connected by two axles and a hinge that are acted upon by gravity.

Plugging the measurements of a particular bicycle into the model revealed its path during motion, like a frame-by-frame animation. An engineer could then use a technique called eigenvalue analysis to investigate the stability of the bicycle as one might do with an aeroplane design. In 1910, relying on such an analysis, the mathematicians Felix Klein and Fritz Noether along with the theoretical physicist Arnold Sommerfeld focused on the contribution of the gyroscopic effect — the tendency of a spinning wheel to resist tilting. Push a bicycle over to the left and the rapidly spinning front wheel will turn left, potentially keeping the bicycle upright.

In April 1970, chemist and popular-science writer David Jones demolished this theory in an article for *Physics Today*[3] in which he described riding a series of theoretically unrideable bikes. One bike that Jones built had a counter-rotating wheel on its front end that would effectively cancel out the gyroscopic effect. But he had little problem riding it hands-free.

This discovery sent him hunting for another force that could be at play. He compared a bike's front wheel to the casters on a shopping trolley, which turn to follow the direction of motion. A bicycle's front wheel can act as a caster because the point at which the wheel contacts the ground typically sits anywhere from 5 centimetres to 10 centimetres behind the steering axis (see 'What keeps a riderless bike upright?'). This distance is known as the trail. Jones discovered that a bike with too much trail was so stable that it was awkward to ride, whereas one with negative trail was a death trap and would send you tumbling the moment you released the handlebars.

When a bicycle starts to topple, he concluded, the caster effect steers the front end back under the falling weight, keeping the bicycle upright. To Jones, the caster trail was the sole explanation for a bike's self-stability. In his memoir, published 40 years later, he counted the observation as one of his great accomplishments. "I am now hailed as the father of modern bicycle theory," he declared.

"EVERYBODY KNOWS HOW TO RIDE A BIKE, BUT NO ONE KNOWS HOW WE RIDE BIKES."

GEARING UP

That article would make an impression on Jim Papadopoulos, then a teenager in Corvallis, Oregon, with a gift for numbers and a home life in tatters. In 1967, his father Michael, an applied mathematician, had moved his wife and four children from England to the United States to start a job at Oregon State University. But Michael Papadopoulos was denied tenure after protesting against the Vietnam War, setting off a decade-long legal battle with the university that left him out of a job and the family scouring rubbish bins for scraps. Jim's mother killed herself in the early 1970s. "Just as I was opening my eyes to the world and deciding who I was," Papadopoulos says, "my family was falling apart."

He found solace in bikes. He pedalled his Peugeot AO8 around town and grew his hair to his shoulders. He stopped going to classes, and his grades took a tumble. At 17, he dropped out of school and left home. But before he abandoned his studies, a teacher gave him the Jones article.

Papadopoulos found it captivating but confusing. "I've got to learn this stuff," he thought. He spent the summer bumming around Berkeley, California, reading George Arfken's textbook *Mathematical Methods for Physicists* in his spare time. Then, he worked at a plywood mill in Eugene, Oregon, earning enough money to buy the legendary Schwinn Paramount that he raced every weekend. In 1973, he worked for the frame builder Harry Quinn in Liverpool, UK, but he was terrible at it and Quinn asked him to leave.

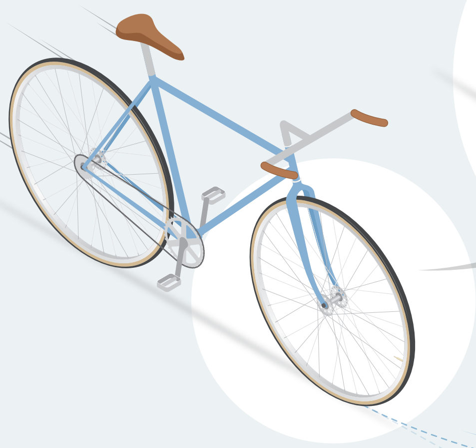
Papadopoulos returned to Oregon, took a

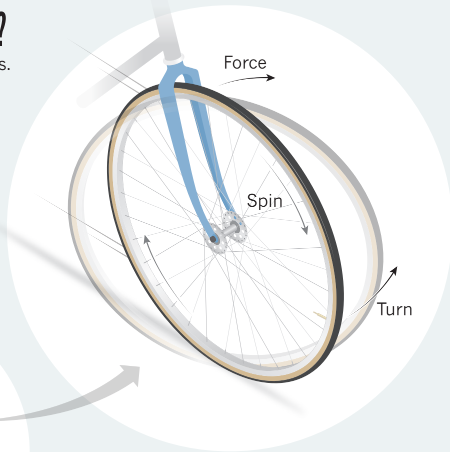
Jim Papadopoulos sees a future with radically new bicycle designs.

ADAM GLANZMAN FOR *NATURE*

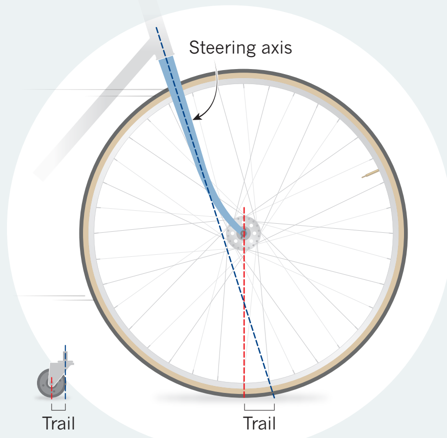
WHAT KEEPS A RIDERLESS BIKE UPRIGHT?

Scientists have grappled with this question for decades. How does a bike moving forward without a rider stay upright? Even when struck from the side, it will correct its course and regain stability.



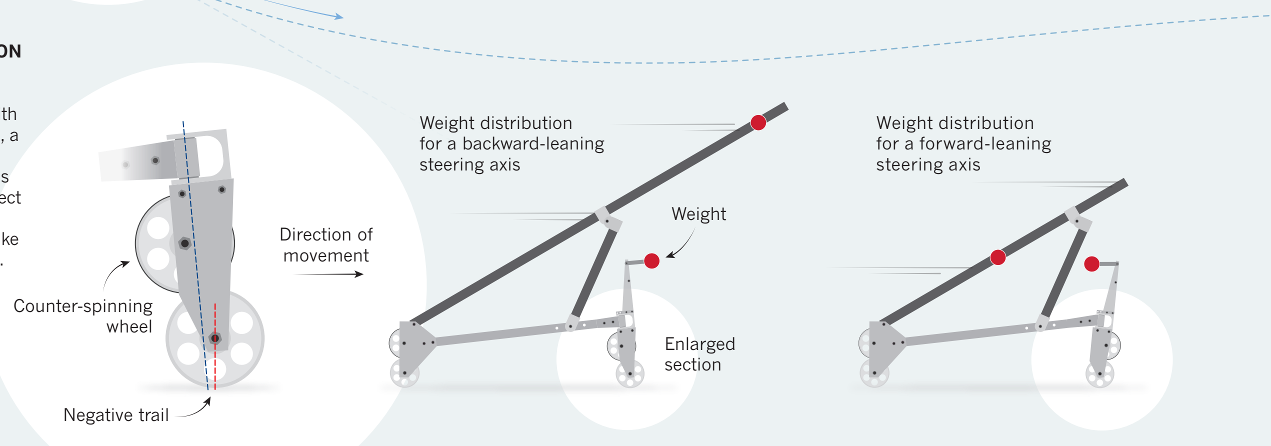


THE GYROSCOPIC EFFECT
A spinning wheel will resist falling over and transfer tilting force into a turn. This could help to right a bike.



THE CASTER TRAIL
A bicycle's front-wheel steering axis sits slightly ahead of the point at which the wheel touches the ground, creating a 'trail' like that of an office-chair caster. This means the wheel will turn in the direction the bike is travelling (or falling, as the case may be).

THE WEIGHT DISTRIBUTION
Bicycle researcher Jim Papadopoulos found these explanations incomplete: with the right weight distribution, a bicycle with a negative trail and counter-spinning wheels to cancel the gyroscopic effect can still be self-stable. His collaborators have built a bike to test some of these ideas[2].



JASIEK KRZYSZTOFIAK/NATURE

few college classes and, in 1975, started undergraduate studies in mechanical engineering at the Massachusetts Institute of Technology (MIT) in Cambridge. He did well. Oil company Exxon later supported him as he studied for a PhD in fracture mechanics. Papadopoulos's adviser, Michael Cleary, was optimistic about his prospects as an academic. "I think Jim will become a university professor — and we certainly hope it's going to be here at MIT," he told a writer from Exxon's in-house magazine.

Papadopoulos had other ideas. He had been studying Whipple's model and Jones's article, and wrote to bike companies offering his services as an engineer. He didn't receive a single response. Instead, Cleary helped him to get a position at the US Geological Survey in Menlo Park, California, where he first met Andy Ruina.

The two became fast friends. When Ruina got a job at Cornell, he hired Papadopoulos as a postdoc. "We talked about bikes all the time, but I didn't realize he wanted to make a serious thing about it," Ruina says.

Papadopoulos convinced Ruina that bicycle companies — like oil companies — might be interested in supporting academic research. So he started fund-raising, reaching out to bike makers. For $5,000, they could be benefactors of the Cornell Bicycle Research Project, an ambitious effort that would investigate everything from the strength of wheels to brake failure in the rain.

Papadopoulos's first goal was to finally understand what makes one bicycle more stable than another. He sat in his office and scrutinized 30 published attempts at writing the equations of motion for a bicycle. He was appalled by the "bad science", he says. The equations were the first step towards connecting the geometry of a bicycle frame with how it handled, but each new model made little or no reference to earlier work, many were riddled with errors and they were difficult to compare. He needed to start from scratch.

After a year of work, he had what he believed to be the definitive set of equations in hand. Now it was time for them to talk back to him. "I was sitting for hours at a time, staring at the equations and trying to figure out what they implied," he says.

He first rewrote the bicycle equations in terms of the caster trail, the crucial variable that Jones had championed. He expected to find that if the trail was negative, the bicycle would be unstable, but his calculations suggested otherwise. In a report that he prepared at the time, he sketched a bizarre bicycle with a weight jutting out in front of the handlebars. "A sufficiently forward [centre of mass] can compensate for a slightly negative trail," he wrote. No single variable, it seemed, could account for self-stability.

This discovery meant that there was no simple rule-of-thumb that could guarantee that a bike is easy to ride. Trail could be useful. Gyroscopic effects could be useful. Centre of mass could be useful. For Papadopoulos, this was revelatory. The earliest frame builders had simply stumbled on a design that felt OK, and had been riding around in circles in that nook of the bicycle universe. There were untested geometries out there that could transform bike design.

THE CRASH

After two years, Ruina could no longer support Papadopoulos. Apart from the bike manufacturer Murray, the only industry donations the two ever got were from Dahon and Moulton, makers of small-wheeled bicycles — perhaps because the bikes' unconventional designs could make them tricky to ride. Ruina joked that he should change the name to the "Folding Bicycle

Research Project". It was gallows humour.

And although Papadopoulos was making progress in the mathematics of bikes, the only article that he ever published as the first author was a book chapter[4]. "I find much more joy discovering the new and working out the details and, of course, it's boring to write it up," he says. Without money or publications, his time in bicycle research wound down. In 1989, he put his bikes into a moving van and drove west to Illinois, where his then-wife had a job. He endured a succession of teaching and industry jobs that he hated. In his spare time, he moderated the Bicycle Science e-mail list for bicycle-science nerds and helped to build a car that fitted into a few suitcases for the reality television show *Junkyard Wars*.

In 2001, David Wilson, an MIT engineer and inventor of one of the first modern recumbent bicycles, invited Papadopoulos to co-author the third edition of the book *Bicycling Science*. Papadopoulos was overwhelmed by monetary debts and responsibilities. He failed to send Wilson the first chapter, and then stopped responding to e-mails altogether. Wilson felt betrayed. "He is a rather brilliant guy," Wilson says, but "he always had problems finishing anything".

BACK TO THE BIKE

At Cornell, Ruina moved on. He applied the team's insights about bicycles to a new arena: robots. If bicycles could demonstrate such elegant stability without a control system, he reasoned, it might be possible to design a stripped-down walking machine that achieves the same thing. In 1998, he worked with Martijn Wisse, a graduate student of Schwab's at the Delft University of Technology in the Netherlands, to build a bipedal machine that could walk down a slight incline with no motor at all, storing energy in its swinging arms. Adding a few electronic motors generated an energy-efficient robot that could walk on level ground.

In 2002, Schwab decided to spend his sabbatical with Ruina, and they started discussing the old bicycle work. It was then that Ruina called Papadopoulos and paid for him to visit. "That was the first time I met the genius," says Schwab.

With more bicycles on the road than ever before, Schwab found it inconceivable that no one had published the correct set of bike equations, or applied it to bicycle design challenges. Within a year, he and Jaap Meijaard, an engineer now at the University of Twente in the Netherlands, independently derived their own equations and found complete concordance with Papadopoulos's. They presented the definitive bicycle equations at an engineering conference in South Korea, and the four collaborators published them jointly[1].

The challenge now was to prove that it was more than just a mathematical finding. Schwab and a student spent a year building a self-stable bike with a very small negative trail. Looking like the offspring of a razor scooter and a see-saw, it had a weight angled out in front of the front wheel and a counter-turning wheel to cancel out gyroscopic effects. In a video of it coasting, you can see it lean and veer to the right, but then recover on its own[2]. The experiment proved that Papadopoulos had been right about the complex interplay of factors that make a bicycle stable or unstable.

Yet, after waiting for three decades for his discoveries to reach a wider audience, Papadopoulos can't help but feel deflated. "It did not change everything in the way that we imagined," he says. This year's bike frames look much like last year's. "Everyone is still in the box," he says. Nevertheless, other researchers have since been pulled into the group's orbit, creating enough momentum to launch a Bicycle and Motorcycle Dynamics conference in 2010. It gathers together tinkerers from all over the world, some of whom have also built weird experimental bicycles to test design principles.

One of the organizers of this year's conference, engineer Jason Moore of the University of California, Davis, has sought to probe the link between a bicycle frame's geometry and an objective measure of handling — its ease of control[5]. The work was inspired by extensive military research on aircraft pilots. Moore created a model of human control by performing various manoeuvres on bikes kitted out with sensors to monitor his steering, lean and speed. To force himself to balance and ride using steering movements alone (rather than shifting his weight), he had to don a rigid upper-body harness that bound him to the bike. The research confirmed the long-standing assumption that more stable bikes handle better, and potentially gives frame builders a tool to optimize their designs.

It also introduced a puzzle: the steering torque required was two or three times that predicted by the Whipple bicycle model[6]. This might have been caused by friction and flexing of the tyres, which are not part of the model, but no one is certain. For further tests, Moore and his colleagues have built a robotic bike that can balance itself. "Once you have a robot bicycle, you can do a lot of crazy experiments without having to put a human in danger," he says. (One of his earlier handling experiments had him regaining his balance after a sideways blow from a wooden stick.) Unlike many other riderless-bike robots, it does not use internal gyroscopes to stay upright, but depends on steering alone. Moore has shipped it to Schwab for further study.

Today, Schwab has the kind of laboratory that Papadopoulos always dreamed of, and Papadopoulos is grateful to be able to collaborate. "It's the most beautiful thing you can imagine," he says. Schwab's other projects include a 'steer by wire' bike, which allows him to separate steering movements from balancing ones, and a 'steer assist' bicycle, which stabilizes itself at slow speeds. He has also identified a rear-steered recumbent bike that shows self-stability, in part owing to an enlarged front wheel that boosts gyroscopic effects. The chief advantage of a rear-steered recumbent is that it would have a shorter chain than standard recumbents, which should lead to better energy transfer. "People have tried to build them before, but they were unrideable," Schwab says.

"ONCE YOU HAVE A ROBOT BICYCLE, YOU CAN DO A LOT OF CRAZY EXPERIMENTS."

Papadopoulos, who now has a teaching position at Northeastern University in Boston, is trying to get comfortable with academia once again. He's establishing collaborations, and testing out long-dormant ideas about why some bicycles wobble at high speed[7]. He believes he can eliminate speed wobble with a damper to soak up vibrations in the seat post. With his new colleagues and students, he is branching out into other types of question, not all them bike-related.

Down in his basement, Papadopoulos opens the drawer of a tan filing cabinet and starts flipping through crinkled manila folders marked with labels such as 'tire pressure', 'biomechanics' and 'Cornell'. He pulls out a textbook. "Exercise physiology? I never really got into that one," he says, tossing it aside. In the back of the drawer, he finds a thick folder of bicycle research ideas, marked 'Unfinished'.

Papadopoulos thinks for a second and then offers a correction: "Mostly unfinished." ■

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